

# Complete one-loop effects of SUSY QCD in $b\bar{b}h$ production at the LHC under current experimental constraints

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## Abstract

Inspired by the recent LHC Higgs data and null search results of supersymmetry (SUSY), we scan the parameter space of the Minimal Supersymmetric Standard Model (MSSM) with relatively heavy sparticles (1-3 TeV). Then in the parameter space allowed by current collider experiments and dark matter detections, we calculate the complete one-loop SUSY QCD corrections to  $pp \rightarrow b\bar{b}h$  at the LHC with  $\sqrt{s} = 14$  TeV and obtain the following observations: (i) For the large values of  $\tan\beta$  and low values of  $m_A$ , the SUSY QCD effects can be quite large, which, however, have been excluded by the latest results of LHC search for  $H/A \rightarrow \tau^+\tau^-$ ; (ii) For modest values of  $\tan\beta$  and  $m_A$  which so far survived all experimental constraints, the SUSY QCD corrections can maximally reach about  $-9\%$ .

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## I. INTRODUCTION

Very recently the ATLAS and CMS collaborations have independently reported the observation of a Higgs-like resonance with a mass about 125 GeV [1]. At the same time, the CDF and D0 collaborations have also updated their combined results for the Higgs searches in  $b\bar{b}$  channel, which support the LHC observation [2]. Since in the Minimal Supersymmetric Standard Model (MSSM) a SM-like Higgs boson is predicted with a mass below 130 GeV, the observation of such a 125 GeV Higgs boson supports SUSY, albeit quite restrictive on the parameter space of SUSY [3].

Meanwhile, the direct searches for SUSY particles (sparticles) have been performed at the LHC. Based on about  $5 \text{ fb}^{-1}$  luminosity, the ATLAS and CMS collaborations have reported null results and obtained some bounds on the sparticle masses, which is about 1 TeV for the gluino and first generation of squarks [4], 330 GeV for the electroweak gauginos, 180 GeV for the sleptons [5], 465 GeV for the stops and 480 GeV for the sbottoms [6]. These bounds indicate that SUSY may be heavier than expected and the sparticles may be significantly heavier than the electroweak scale [7, 8].

In case that the sparticles are heavy and beyond the LHC scope of direct production, search for the indirect SUSY effects via loop corrections will be of great importance. Since the loop effects of heavy sparticles are usually small, we should look for some processes in which the heavy sparticles have non-decoupling loop effects. One type of such processes are Higgs productions at the LHC, such as the production of  $tH^-$  and  $hb\bar{b}$ , in which the heavy sparticles have sizable non-decoupling loop effects for a small value of  $m_A$  and a large value of  $\tan\beta$  [9, 10] (when  $m_A$  getting large, such effects will vanish). The reason for these non-decoupling effects is that the couplings in the loops are proportional to some SUSY mass parameters and can be enhanced by the large values of  $\tan\beta$ .

In this note we focus on the production of  $hb\bar{b}$  at the LHC and calculate the complete one-loop SUSY QCD corrections to this process. As an important Higgs production channel for the MSSM, this production has been studied in the literature [10], where the non-decoupling SUSY QCD effects are found to be large (reach -40% for  $\tan\beta = 30$ ). We revisit this production for the following reasons: Firstly, in the literature the SUSY QCD corrections to this process are calculated only partially (only the corrections to the  $hb\bar{b}$  vertex have been considered). The complete one-loop corrections involve pentagon Feynman diagrams,

whose calculations are rather complicated and have not been performed. Secondly, the CMS collaboration has recently measured this channel and given constraints on the plane of  $\tan\beta$  versus  $m_A$  [11]. Since the non-decoupling SUSY QCD effects in this production is sensitive to the values of  $\tan\beta$  and  $m_A$ , we should update the calculations by considering such new constraints. Moreover, other experimental constraints, such as the dark matter direct detection limits and the SM-like Higgs boson mass around 125 GeV, are also rather restrictive and should be considered. In this work, we consider all current experimental constraints to scan the MSSM parameter space and then in the allowed parameter space we calculate the process  $pp \rightarrow b\bar{b}h$  with the complete one-loop SUSY QCD corrections.

The paper is organized as follows. In Sec. II. we describe the calculations for the process  $pp \rightarrow b\bar{b}h$ . In Sec.III we show numerical results. Finally, we draw the conclusions in Sec. IV.

## II. THE DESCRIPTION OF CALCULATIONS

In the MSSM the lighter CP-even Higgs mass ( $m_h$ ) is smaller than  $M_Z$  at tree level but receives large corrections at the loop level. The leading part of the corrections is from the stop sector and can be expressed as [13]

$$\Delta m_h^2(\tilde{t}) \simeq \frac{3m_t^4}{2\pi^2 v^2 \sin^2\beta} \left[ \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{X_t^2}{2m_{\tilde{t}_1} m_{\tilde{t}_2}} \left( 1 - \frac{X_t^2}{6m_{\tilde{t}_1} m_{\tilde{t}_2}} \right) \right] \quad (1)$$

where  $X_t = A_t - \mu \cot\beta$  is the stop mixing parameter. We see that a large stop mass or a large stop mixing parameter is needed to increase  $m_h$  to 125 GeV. In our calculations we consider the collider constraints on the MSSM Higgs sector, using the packages **FeynHiggs2.8.6** [14] and **HiggsBounds-3.8.0**[15] to calculate the observables in the Higgs sector and require them to satisfy the constraints from the LEP, Tevatron and LHC.

The SUSY QCD corrections to  $h b\bar{b}$  production at the LHC involve the sbottoms and gluino in the loops. The sbottom mass matrix takes the form [16]

$$M_{\tilde{b}}^2 = \begin{pmatrix} m_{\tilde{b}_L}^2 & m_b X_b^\dagger \\ m_b X_b & m_{\tilde{b}_R}^2 \end{pmatrix}, \quad (2)$$

where

$$m_{\tilde{b}_L}^2 = m_{\tilde{Q}}^2 + m_b^2 - m_Z^2 \left( \frac{1}{2} - \frac{1}{3} \sin^2 \theta_W \right) \cos(2\beta) , \quad (3)$$

$$m_{\tilde{b}_R}^2 = m_{\tilde{D}}^2 + m_b^2 - \frac{1}{3} m_Z^2 \sin^2 \theta_W \cos(2\beta) , \quad (4)$$

$$X_b = A_b - \mu \tan \beta , \quad (5)$$

where  $m_{\tilde{Q}}^2$  and  $m_{\tilde{D}}^2$  are respectively the soft-breaking mass parameters for the left-handed squark doublet  $\tilde{Q}$  and the right-handed down squark  $\tilde{D}$ ,  $A_b$  is the sbottom soft-breaking trilinear coupling and  $\mu$  is the SUSY-preserving bilinear coupling of the two Higgs doublets in the superpotential. This mass matrix can be diagonalized by a unitary transformation which rotates the weak eigenstates  $\tilde{b}_{L,R}$  to the mass eigenstates  $\tilde{b}_{1,2}$ ,

$$\begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{b}} & \sin \theta_{\tilde{b}} \\ -\sin \theta_{\tilde{b}} & \cos \theta_{\tilde{b}} \end{pmatrix} \begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \end{pmatrix} \quad (6)$$

with the sbottom masses  $m_{\tilde{b}_{1,2}}$  and the mixing angle  $\theta_{\tilde{b}}$  determined by

$$m_{\tilde{b}_{1,2}} = \frac{1}{2} \left[ m_{\tilde{b}_L}^2 + m_{\tilde{b}_R}^2 \mp \sqrt{\left( m_{\tilde{b}_L}^2 - m_{\tilde{b}_R}^2 \right)^2 + 4m_b^2 X_b^2} \right] , \quad (7)$$

$$\tan 2\theta_{\tilde{b}} = \frac{2m_b X_b}{m_{\tilde{b}_L}^2 - m_{\tilde{b}_R}^2} . \quad (8)$$

We produce the one-loop amplitudes with **FeynArts-3.5** [17] and use the **FormCalc-6.1** [18] to simplify them and express the loop functions defined in [19]. The numerical calculations are performed by using **LoopTools-2.2** [20]. In order to preserve supersymmetry, we adopt the constrained differential renormalization (CDR) [21] to regulate the ultraviolet divergence (UV) in the self-energy and vertex corrections, which is equivalent to the dimensional reduction method at one-loop level [22]. In Fig.1 we display the representative pentagon Feynman diagrams for the SUSY QCD corrections in the subprocesses  $gg \rightarrow b\bar{b}h$ . Due to no massless particles in the loop, all the Feynman diagrams with the gluino and sbottoms in the loops are infrared (IR) finite.

In our calculations, we assume a common SUSY mass  $M_{SUSY}$  defined by  $M_{SUSY} = M_{\tilde{Q}} = M_{\tilde{U}} = M_{\tilde{D}} = M_{\tilde{g}} = A_t = A_b = \mu$ . We fix slepton mass parameters  $M_{\tilde{L}} = M_{\tilde{E}} = A_\tau = 3$  TeV and scan the following MSSM parameter regions:

$$5 \leq \tan \beta \leq 60, \quad 90 \text{ GeV} \leq M_A \leq 350 \text{ GeV}, \quad 1 \text{ TeV} \leq M_{SUSY} \leq 3 \text{ TeV} \quad (9)$$

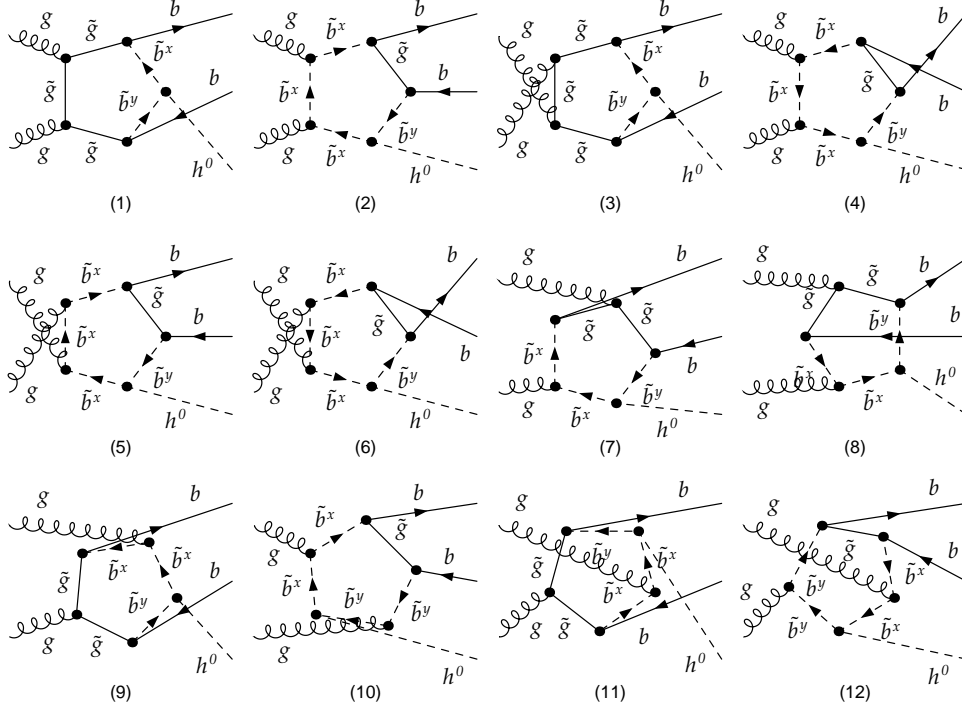


FIG. 1: The pentagon diagrams for SUSY QCD corrections to the subprocess of  $gg \rightarrow b\bar{b}h$  at the LHC.

In our scan we consider the following constraints on the parameter space: (i) We require that the SM-like Higgs is in the region of  $120 \text{ GeV} < m_h < 130 \text{ GeV}$ ; (ii) For the constraints from flavor physics and electroweak precision data, we checked by using the package `susy_flavor` v2.0 [23] that they are safely satisfied because we assume relatively heavy sparticles. (iii) We consider the dark matter constraints from the WMAP relic density and the direct detection results by using the package `MicrOmega` v2.4 [24].

### III. NUMERICAL RESULTS

Since the b-quark Yukawa coupling may receive large radiative corrections in the MSSM, we use the running b-quark mass ( $m_b^{\overline{DR}}$ ) and use the method induced in [26] to absorb the MSSM corrections into the effective b-quark Yukawa couplings. But for the b-quark in the final state, we take the pole mass to assure the correct on-shell behavior.

In our numerical calculations, we take the input parameters of the SM as [27]

$$m_t = 172 \text{ GeV}, \quad m_b^{\overline{MS}}(m_b^{\overline{MS}}) = 4.19 \text{ GeV}, \quad m_Z = 91.1876 \text{ GeV}, \quad \alpha(m_Z) = 1/127.918$$

Here  $m_b^{\overline{MS}}(m_b^{\overline{MS}})$  is the QCD- $\overline{MS}$  bottom-quark mass, which is related to  $m_b^{\overline{DR}}$  as

$$m_b^{\overline{DR}} = m_b^{\overline{MS}} \left[ 1 - \frac{\alpha_s}{3\pi} - \frac{\alpha_s^2}{144\pi^2} (73 - 3n_f) \right] \quad (10)$$

where  $n_f$  is the number of the active quark flavors. For the strong coupling constant  $\alpha_s(\mu)$ , we take its 2-loop evolution with QCD parameter  $\Lambda^{n_f=5} = 226$  MeV and get  $\alpha_s(m_Z) = 0.118$ . We use CTEQ6L1 and CTEQ6M [28] parton distribution functions (PDF) for the SM tree level and SUSY QCD one-loop level computations, respectively. The renormalization scale  $\mu_R$  and factorization scale  $\mu_F$  are chosen to be  $\mu_R = \mu_F = m_Z$ . We numerically checked that all the UV divergence in the loop corrections canceled.

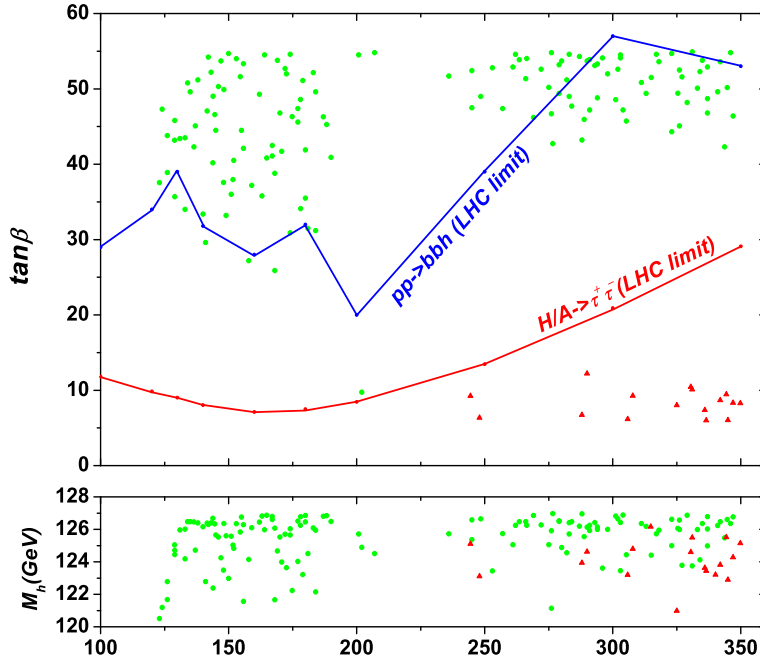


FIG. 2: The scatter plots of the samples satisfying constraints (i)-(iii), projected on the planes of  $\tan\beta$  and  $M_h$  versus  $m_A$ . The curves denote the bounds from the measurements of  $pp \rightarrow H/A \rightarrow \tau^+\tau^-$  and  $pp \rightarrow b\bar{b}h(h \rightarrow b\bar{b})$  at the LHC (the region above each curve is excluded), The triangles (red) represent the samples survived all the constraints.

In Fig.2 we project the survived samples satisfying the constraints (i)-(iii) on the planes of  $\tan\beta$  and  $M_h$  versus  $m_A$ . It can be seen that they spread in three different regions: the non-decoupling regime ( $m_A < 200\text{GeV}$ ,  $\tan\beta > 20$ ), the decoupling regime with a large  $\tan\beta$  ( $m_A > 200\text{GeV}$ ,  $\tan\beta > 40$ ) and the decoupling regime with a small  $\tan\beta$  ( $m_A < 200\text{GeV}$ ,  $\tan\beta < 15$ ). In this figure we also show the bounds from the Higgs searches  $pp \rightarrow H/A \rightarrow \tau^+\tau^-$  [12] and  $pp \rightarrow b\bar{b}h$  at the LHC [11]. We can see that the constraint

from the  $\tau^-\tau^+$  channel is much stronger than  $pp \rightarrow b\bar{b}h$  and two regimes with a large  $\tan\beta$  have been excluded. Only the decoupling regime with a small  $\tan\beta$  is still allowed, where the SM-like Higgs can get a correct  $m_h \sim 125 \pm 2$  due to the contribution of heavy stops.

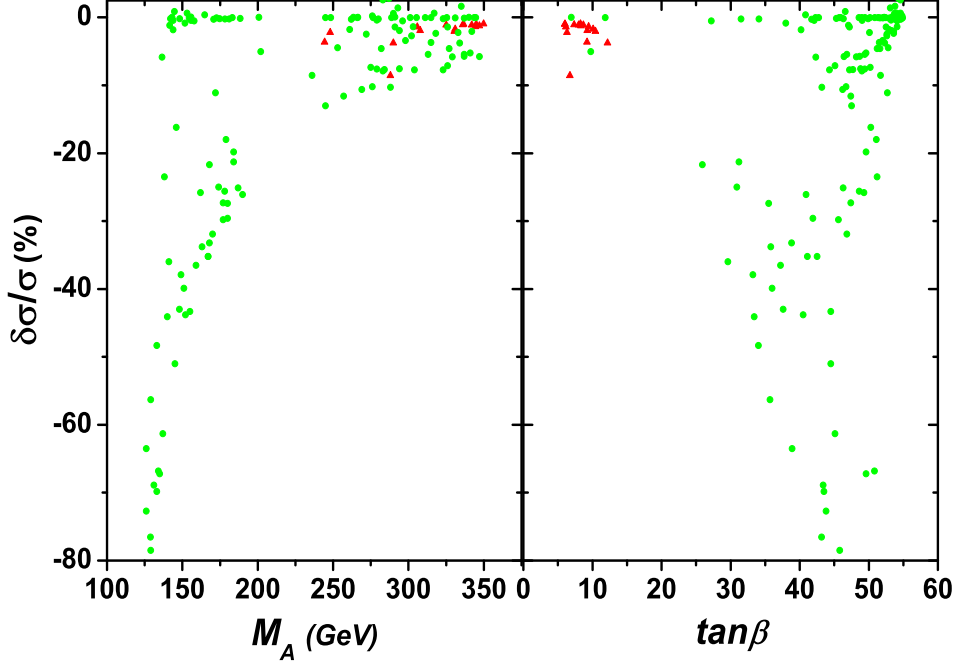


FIG. 3: Same as Fig.2, but showing the one-loop SUSY QCD corrections.

In Fig.3 we present the one-loop SUSY QCD corrections to the process  $pp \rightarrow b\bar{b}h$  for the samples displayed in Fig.2. We can see that the SUSY QCD corrections will be significant for the samples which have a large  $\tan\beta$  and a low value of  $m_A$ . This can be understood by the contribution to the effective b-quark Yukawa coupling after integration of the heavy sparticles, which is  $\delta\bar{y}_{hb\bar{b}} = -\frac{g\alpha_s m_b^{\overline{MS}} \sin\alpha}{6\pi m_W \cos\beta} (\frac{M_{\tilde{g}}\mu}{M_{SUSY}^2}) [\tan\beta + \cot\alpha]$  [8]. Since we assume  $M_{SUSY} = M_{\tilde{g}} = \mu$ , the Yukawa coupling will be independent of the sparticle masses and be greatly enhanced by a large  $\tan\beta$ . However, it should be noted that these samples will lead to the excess of the production rate of  $pp \rightarrow H/A \rightarrow \tau^+\tau^-$  and thus have been excluded by the current measurements. With the increase of  $m_A$  and the decrease of  $\tan\beta$ , the corrections drop rapidly and approach zero in the decoupling limit. The main reason is that  $\delta\bar{y}_{hb\bar{b}}$  can be heavily reduced by the cancellation between  $\tan\beta$  and  $\cos\alpha$ , which have a relation as  $\cot\alpha \simeq -\tan\beta - 2m_Z^2 \tan\beta \cos^2\beta / m_A^2$  for a large  $m_A$ . For the samples which survived all the constraints, the SUSY QCD corrections can only reach about  $-9\%$  at the LHC with  $\sqrt{s} = 14$  TeV. Detecting such a size of SUSY QCD effects may be challenging in the future measurement of the process  $pp \rightarrow b\bar{b}h$  [29].

## IV. CONCLUSION

In this work, we calculated the complete one-loop SUSY QCD corrections to the process  $pp \rightarrow b\bar{b}h$  at the LHC with  $\sqrt{s} = 14$  TeV. We found that the large SUSY QCD corrections in the non-decoupling regime with a large  $\tan\beta$  and a low  $m_A$  has been excluded by the latest results of LHC non-standard Higgs searches. For the survived decoupling regime which have modest values of  $\tan\beta$  and  $m_A$ , the SUSY QCD corrections can maximally reach  $-9\%$ .

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